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Two phase flow pattern for propane in a horizontal smooth tube

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Abstract

In this paper, an experimental study on two-phase flow patterns (evaporation) for propane in a horizontal smooth tube is presented. The tests were conducted at various saturation pressures from 0.2 MPa to 0.4 MPa for different mass velocities from 70 kg/(m^2·s) to 180 kg/(m^2·s) and two heat fluxes (20.16 kW/m^2 and 37.1 kW/m^2) in the entire ranges of vapour qualities. Several flow pattern maps were compared with the experimental flow pattern data, especially for the intermittent/annular (I/A) transition line. Finally, a transition equation of intermittent/annular flow for propane was modified with an improved flow pattern map.

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Keywords: Flow boiling; Evaporation; Flow pattern; Flow pattern map; Experiment; Horizontal tube; Propane

1. Introduction

Due to environmental problems of traditional chlorinated refrigerants, it has become an urgent task to search for suitable substitutes in the refrigeration industry. Propane is considered as an environment-friendly and potential refrigerant to replace R22 and R502 (James et al., 1992). The heat transfer characteristics of propane, such as two-phase pressure drops and heat transfer coefficients, play important parts in evaluating and optimizing performance of

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refrigeration cycles. The prediction of local flow pattern is essential to calculate two-phase pressure drops and heat transfer coefficients in refrigerant systems.

The Taitel and Dukler (1976) flow pattern map is one of the most comprehensive treatments of flow pattern transitions in horizontal flow on a semi-theoretical basis. Steiner (1993) proposed a modified flow pattern map by the experiments of R12 and R22 based on the Taitel and Dukler map. Then, the Kattan-Thome-Favrat (1998) flow pattern map was obtained based on the tests for R134a, R123, R402a, R404a and R502 under flow boiling conditions by modification of the Steiner map. The influences of heat flux and dryout were considered in this map. Wojitan et al. (2005) extended the Kattan-Thome-Favrat map to cover the dryout region between the annular and mist flow regimes and subdivided the stratified-wavy region into three subzones: slug, slug/stratified-wavy and stratified-wavy. Barbieri et al. (2008) defined a new intermittent/annular transition curve based on R134a in smooth tubes of internal diameters varying from 6.2 mm to 12.6 mm. It was found that the intermittent/annular transition depended on the liquid Froude number and Martinelli parameter including the effects of mass velocity, vapor quality and inner tube diameter. Costa-Patry and Thome (2013) developed a new intermittent/annular transition equation considering the effect of the heat flux for micro-channels .

The objective of this paper is to present data related to the observed flow patterns of propane (evaporation) in a smooth horizontal tube and compare several flow pattern maps with the experimental data. A modified transition equation is proposed from intermittent to annular flow.

Nomenclature

x	vapour quality
Q	thermal power, W
C_p	specific heat capacity, J/(kg·K)
G	mass velocity, kg/(m^2·s)
p	pressure, MPa
T	temperature, K
H_{lv}	latent heat, J/kg
Fr	liquid Froude number
X_{tt}	Martinelli parameter
D	tube diameter, m
g	gravitational acceleration, m/s^2
Greek letters	
ρ	density, kg/m^3
μ	dynamic viscosity, Pa·s
Subscripts	
in	inlet of the test section
preh	preheater
sub	sub-cooled state
l	liquid phase
v	vapour phase

2. Experimental apparatus

2.1. Test facility

Fig. 1 shows the schematic diagram of the experimental apparatus. A detailed description of the test facility was given in the previous work (Wang et al., 2014; Zou et al., 2010). Two sight glasses with 6 mm inner diameters and 100 mm lengths are located at the inlet and outlet of the heat transfer test section. The flow patterns were recorded by a Motion Studio high speed camera system with highest shooting frequency of more than 10000 FPS and the minimum exposure time of 1 μs combining with a laser constant cold light source.

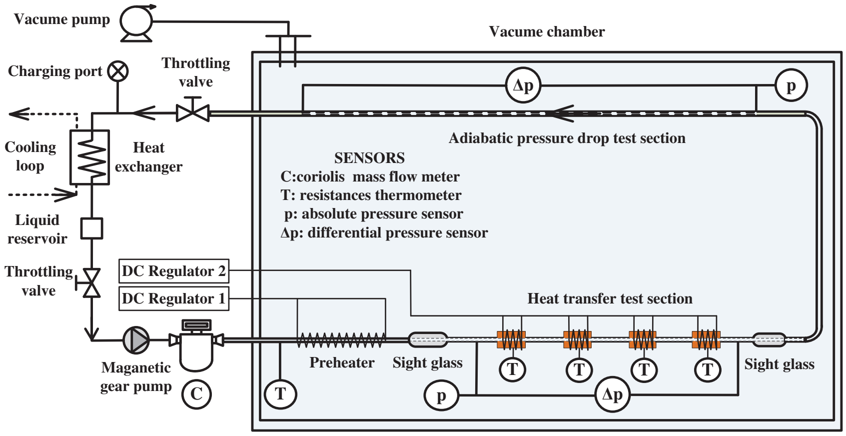


Fig. 1. Schematic view of the experimental apparatus.

2.2. Data reduction

The vapor quality entering the heat transfer test section is obtained from an energy balance between the enthalpy increment of the fluid and the thermal power input. The expression for vapor quality is listed as follows:

$$x_{\mathrm{in}} = \frac{Q_{\mathrm{preh}} - C_{\mathrm{p}} G (T_{\mathrm{in}} - T_{\mathrm{sub}})}{G H_{\mathrm{lv}}}, \tag{1}$$

where Q_{preh} is the electrical heat power in the preheater; T_{sub} is the inlet temperature of the subcooled liquid refrigerant in the preheater; G is the mass velocity; C_{p}, H_{lv} and T_{in} are the specific heat capacity, the latent heat and the fluid saturation temperature at the inlet of the heat transfer test section, respectively. T_{in} is obtained from Refprop 8.0 (Lemmon et al., 2007) corresponding to the local saturation pressure. The local saturation pressure is determined by an absolute pressure sensor set at the inlet of the heat transfer test section and a linear pressure drop assumption with a differential pressure sensor along the test section.

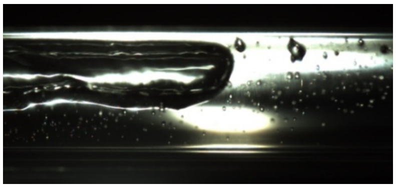
The instruments and uncertainties for the present experiments are summarized in Table 1.

Table 1. Parameters and estimated uncertainties.

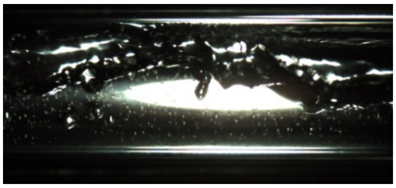
Parameters	Instruments	Range	Uncertainties
Temperature (K)	Pt100 thermometer	80-300	0.1 K
Absolute pressure (MPa)	UNIK 5000 pressure transducer	0-1	0.04 %
Differential pressure (kPa)	UNIK 5000 differential pressure transducer	0-40	0.04 %
Mass flow (kg/h)	ULTRA mass MKII Coriolis mass flowmeter	0-180	0.1 %
Voltage (V)	Keithley 2700 multimeter	0-60	0.005 %
Direct current (A)	ZW 1659 amperometer	0-5	0.2 %

3. Results and analysis

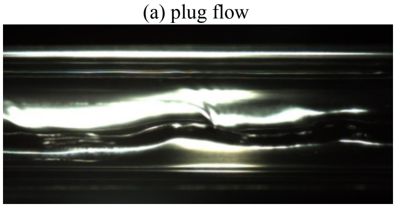
Experiments for propane were carried out at saturated pressures from 0.2 MPa to 0.4 MPa, mass velocities from 70 kg/(m^2·s) to 180 kg/(m^2·s) and heat fluxes of 20.16 kW/m^2 and 37.1 kW/m^2 in the entire ranges of vapor qualities. Within the range of the present tests, four flow patterns have been observed: plug flow, slug flow, stratified-wavy flow (SW) and annular flow (A). Fig. 2 shows the photographs of those flow patterns. In this paper, slug flow and plug flow are classified together as intermittent flow (I) in the flow pattern maps for simplicity. In addition, SW/I means the transition between annular and stratified-wavy flow, while I/A means the transition between intermittent and annular flow.



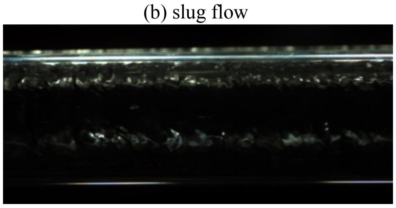
(a) plug flow



(b) slug flow



(c) stratified-wavy flow



(d) annular flow

Fig. 2. Photographs of observed flow patterns: (a) plug flow; (b) slug flow; (c) stratified-wavy flow; (d) annular flow.

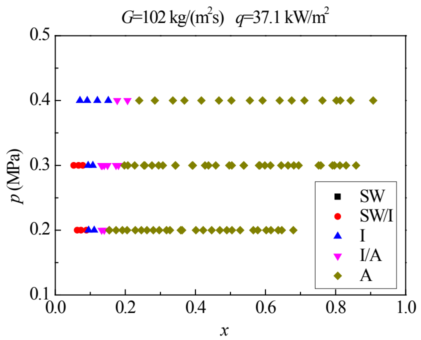


Fig. 3. Variation of observed flow patterns with saturation pressures for propane at G=102 kg/(m^2·s), q=37.1 kW/m^2.

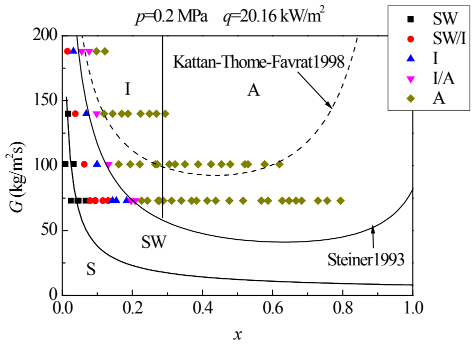


Fig. 4. Comparisons between the experimental data and the Steiner (1993) and Kattan-Thome-Favrat (1998) flow pattern maps for propane at p=0.2 MPa and q=20.16 kW/m^2.

Fig. 3 gives variation of observed flow patterns with saturation pressures for propane at G=102 kg/(m^2·s), q=37.1 kW/m^2. It is illustrated that the transition vapor quality from intermittent to annular flow increases with the rise of saturation pressure, but the effect is not obvious. Fig. 4 presents the comparisons between the experimental data and the Steiner (1993) and Kattan-Thome-Favrat (1998) flow pattern maps for propane at p=0.2 MPa and q=20.16 kW/m^2. It is found that the flow pattern map of Steiner contains more experimental data than that of Kattan-Thome-Favrat. The transition mass velocities from stratified-wavy to annular flow predicted by Kattan-Thome-Favrat map is higher than that from the experiments, and the transition vapor qualities predicted by both flow pattern maps from the stratified-wavy to intermittent flow are also higher than the experimental data. The intermittent/annular transition vapor qualities from the two flow pattern maps are a constant, while the value is changed at different mass velocities in this study.

Barbieri et al. (2008) indicated that the intermittent/annular transition depended on the parameters such as mass velocity, vapor quality and inner diameter. Meanwhile, two non-dimensional groups including the above parameters, the liquid Froude number Fr_l and the Martinelli parameter X_tt, were proposed by the following expressions:

$$Fr_\mathrm{l} = \frac{\left[G\left(1-x\right)\right]^2}{\rho_\mathrm{l}^2 gD} \tag{2}$$

$$X_\mathrm{tt} = \left(\frac{1-x}{x}\right)^{0.875}\left(\frac{\rho_\mathrm{v}}{\rho_\mathrm{l}}\right)^{0.5}\left(\frac{\mu_\mathrm{l}}{\mu_\mathrm{v}}\right)^{0.125} \tag{3}$$

In the above work, it was also found that the intermittent/annular transition curve could be expressed by a correlation of the kind: $Fr_\mathrm{l}=f(X_\mathrm{tt})$. The transition equation from intermittent to annular flow for R134a given by Barbieri et al. is defined as: $Fr_\mathrm{l}=3.75X_\mathrm{tt}^{2.40}$. In Fig. 6, it is noted that the tendency to the intermittent/annular transition predicted by Barbieri et al. is the same to the experiments, but the transition vapor quality predicted is higher than the experimental data.

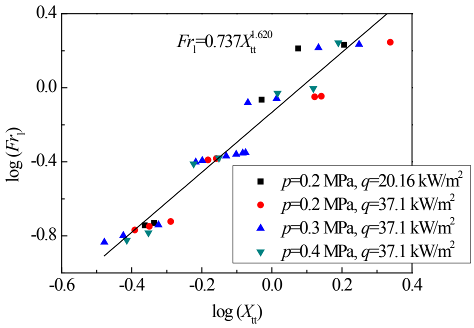
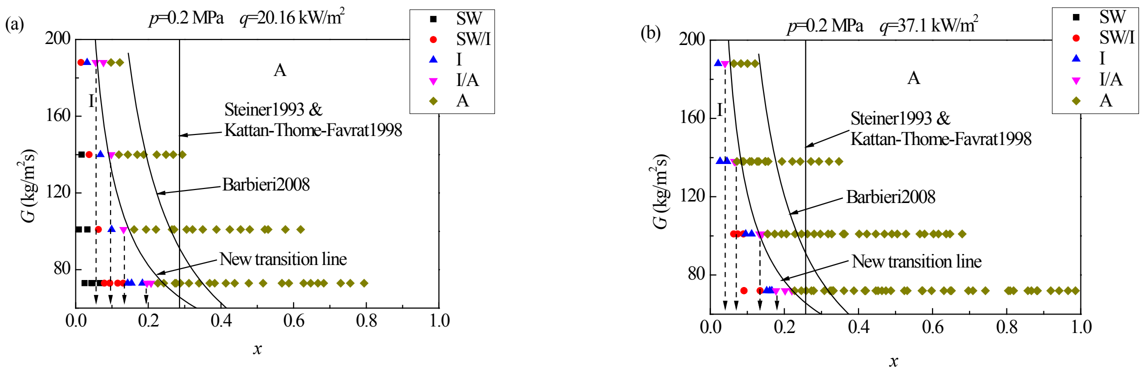


Fig. 5. Plot of data points related to the intermittent/annular transition in terms of the non-dimensional groups log(Fr_l) and log(X_tt).

Fig. 5 displays the plot of data points to the intermittent/annular transition in terms of the logarithmic liquid Froude number and the logarithmic Martinelli parameter. The expression which is $Fr_\mathrm{l}=0.737X_\mathrm{tt}^{1.620}$ has been obtained by curve fitting the data points of the plot of Fig. 5. The new intermittent/annular transition lines obtained by the above equation are also displayed in Fig. 6 at various experimental conditions. It is found that the new transition lines are satisfactory for all of the experimental conditions in the present study. Moreover, it is noted that the transition vapor quality from intermittent to annular flow decreases with the rise of mass velocity which was also found by Barbieri et al. (2008). And it is found that the transition vapor quality from intermittent to annular flow decreases with the rise of heat flux by comparing Fig. 6 (a) with (b), and the influence is more obvious for high mass velocity.



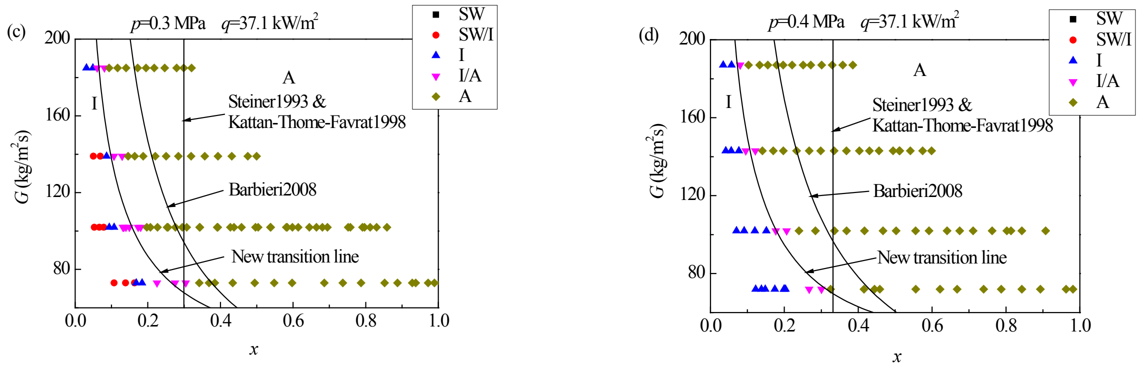


Fig. 6. Comparisons among Steiner & Kattan-Thome-Favrat, Barbieri and new intermittent/annular transition lines at various experimental conditions.

4. Conclusion

This paper presented the observations on flow patterns for propane over a wide range of pressures, vapor qualities and mass velocities. The flow patterns obtained in this paper were compared with the Steiner and Kattan-Thome-Favrat flow pattern maps. The results showed that the flow pattern map of Steiner contained more experimental data than that of Kattan-Thome-Favrat. However, both maps exhibited poor accuracy for the intermittent/annular transition. Moreover, it is noted that the tendency to the intermittent/annular transition predicted by Barbieri et al. (2008) is the same to the experiments, but the transition vapor quality predicted is higher than the experimental data. A modified transition equation was proposed from intermittent to annular flow based on Barbieri et al. The intermittent/annular transition in this work was predicted well by the new equation.

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